FERMILAB-Proposal-0739

Revision of Proposal P-739 for Consideration in the April 1985 PAC Meeting

Crystal-Assisted Elementary Processes:

Radiation, Pair Creation, Trident Production

and Photon Splitting

M.S. Alam, N. Cue, C. Fusina, I.J. Kim, J.C. Kimball

B.B. Marsh, R. Wijayawardana and C.R. Sun

Department of Physics
State University of New York at Albany
Albany, NY 12222

G. Bologna*, M. Gouanere, J.P. Peigneux,

D. Sillou and M. Spighel

Laboratoire de'Annecy-le-Vieux de Physique
des Particules et IN2P3
B.P. 909, F-74019 Annecy-le-Vieux Cedex
France

R. Carrigan, Jr., T. Toohig and S. Baker

Fermi National Laboratory
Batavia, IL 60510

A. Belkacem, M. Chevallier, M.J. Gaillard,

R. Kirsch, J.C. Poizat and J. Remillieux

Institute de Physique Nucleaire et IN2P3
University Claude Bernard, Lyon I
F-69622 Villeurbanne Cedex
France

*Permanent Address: Instituto di Fisica Generale, Corso M. D'Azeglio 46, I10125 Torino, Italy.

Spokesmen

N. Cue (Tel: 518-457-8333)
C.R. Sun (Tel: 518-457-8028)

39 pgs.

I. Background

A high speed particle travelling along a row of atoms in a crystallographic direction experiences essentially an electric field which is transverse to the atomic row. The field strengths can be enormous when compared with fields obtained from other laboratory sources. For example, along the <100> axis of a W crystal cooled to $77^{o}K$, a value as large as 6×10^{13} V/m can be realized. An aligned crystal thus provides a miniature laboratory for investigating(1-4) strong field QED (and perhaps electroweak) processes. Strong field processes are believed to be important in astrophysics, but until now the theory(5) has been developed without the aid of experiments.

The purpose of the original P-739 proposal was to confirm the then newly predicted(1) process of crystal-assisted pair creation (CAP). Since its submission, a similar proposal was accepted at CERN and an experiment (NA33) was performed in July 1984. The results of this CERN experiment, using tagged photons of 50-100 GeV directed along the <110> axis of a LN_2-cooled Ge crystal, confirmed all the essential predictions for CAP, excepting for the magnitude which was observed to be too small by a factor of 3. Figure 1 shows the measured enhancement of the pair creation yield. The increasing yield with increasing photon energy is characteristic of CAP. Crystal-assisted radiation (CAR) of 150-GeV electrons was also investigated(7) in the same CERN run. As with the earlier measurements(8) of 4 to 17-GeV positrons along diamond <110>, excellent agreements with the CAR predictions(9) based on the synchrotron formalism were obtained. Figure 2 shows these agreements for the radiated energy of 150 GeV electrons in cooled Ge <110>. Collectively, these experimental results provide a compelling argument for the validity of viewing an aligned crystal as a distribution of transverse electric fields. Also, they give substance to a recent suggestion[(10)] that the CAP principle could be used to develop an improved γ-ray telescope. In principle, an aligned crystal could pinpoint, with unprecedented accuracy, the sources of ultrarelativistic radiation in interstellar space.

An additional run has been approved at CERN for June-July 1985. The main purposes are to check the previous results with improved set-up and instrumentation, and to examine in greater detail the variation of CAR and CAP yields with alignment angle and crystal thickness. Crystal-assisted trident production[(4)] (CAT) will also be measured for the first time.

Higher beam energies, which are presently available only at Fermilab, would enable us to search for new crystal-assisted processes, and test the theory in a truly high-field regime. The need for higher beam energies can be most easily shown for the case of perfect alignment and negligible beam angular divergence. In this case, a uniform field approximation is adequate[(2-4)] and the characteristic parameter is that of the strong field QED;

$$\chi = \frac{4}{3}\,[\gamma E^*/137^3],$$

where γ is the beam energy in units of electron rest mass and E^* is the electric field strength in atomic units. For example, in CAP, the total rate for a given E^* is proportional to

$$\chi K_{1/3}^{2} (\chi),$$

where $K_{1/3}$ is the modified Bessel function. For $\chi < 1$, this function increases exponentially with increasing χ, reaches a maximum at $\chi \sim 6$, and then decreases as $\chi^{-1/3}$ as $\chi > 10$. With 400-600 GeV photons incident on LN_2-cooled Ge <110>, the region near the predicted maximum rate can be experimentally studied.

Also, previous studies have focused on the axial case. The planar channeling geometry is interesting since photons from CAR, and electrons and positrons from CAP, are predicted to be plane polarized[11]; thus crystal-assisted processes have potential applications in high energy physics. Because the field strengths near crystal planes are generally only ~1/10 those of the corresponding axes, significant yield for planar CAP can be expected only with the energies currently available at Fermilab. Confirmation of the predicted rates is desirable before any serious attempt is made to measure the polarization, since such an experiment will be more time consuming. Additionally, the higher energy at Fermilab makes it feasible to investigate the $\gamma \rightarrow 2\gamma$ photon splitting process[4,12] (CAS) which has been predicted, but never experimentally confirmed.

The possibility of electroweak process in the crystal field such as the inverse beta decay $e^- \rightarrow \mu^- \nu_\mu \nu_e$ has been suggested(4). However, this process requires an electron energy of at least 5 TeV to proceed. Recently Lasukov and Vorobiev(13) (LV) described the equivalent process of $e^- \rightarrow e^- \nu\nu$ which is easier to observe because no kinematic threshold is involved. The rate they computed, using a V-A vertex and channeling wavefunctions for the electron, scales with beam energy as γ^4 and is sufficiently large for measurement at the highest energy available at Fermilab. However, the same process has been examined earlier(17,18) in a uniform magnetic field. Applying the uniform field description to the crystal yields a rate many orders of magnitude smaller than the corresponding LV rate. Indeed, Baier and Katkov(17) give an energy scaling of γ^4 for $\chi << 1$ and $\sim\gamma$ for $\chi >> 1$. This suggests that perhaps the LV result is valid only for the region of $\chi << 1$, but the large discrepancy in the magnitude still remains. We believe the much smaller rate predicted by the uniform field approximation, and thus the detection of these crystal-assisted neutrino events is currently impractical.

II. Proposed Measurements and Justifications

We propose to measure CAR, CAP, CAT and CAS rates at the highest beam energy available for electrons (~800 GeV) and photons (~600 GeV) at Fermilab. A single set-up, shown schematically in Figure 3, will suffice for all these measurements. This set-up can be easily superimposed on the existing TPB facility at Fermilab. For example, the existing tagging system can be utilized with lead glass detectors added for muon and hadron discriminations. The target chamber, consisting of a single crystal mounted on a precision two-axis goniometer, and magnet M2 can be inserted between the existing shielding wall and the large pair spectrometer. This large pair spectrometer will not be used. Instead, another spectrometer with the in-line detector will be assembled and placed behind the existing one. Insertable CS1 and CS2 detectors, each consisting of alternating layers of thin Pb converter and plastic scintillator, are intended for discriminating photon multiplicity.

With the electron beam, CAR and CAT can be measured simultaneously. With the photon beam, CAP and CAS measurements differ only in that S_b and CS1 will be inserted into the beam line for CAS. In this case, S_b vetoes all charged particles originating from the crystal, and CS1 together with the pair spectrometer provide positive signals for conversion events from which we can discriminate one and two photon events.

Germanium single crystals will be used since we have on hand several thicknesses (0.1 - 5 mm) which have been tested to have mosaic spreads of <10 μrad. Tungsten, with much larger field strengths, will also be tried if a sufficiently good quality crystal can be obtained at the time of the experiment.

Experimentally, crystal-assisted processes are readily identified:

1. The rates decrease when the crystal axis or plane is tilted away from the incident beam direction. At sufficiently large angles, the crystal cannot be properly described as a source at large transverse electric fields, because in that case the

rates are governed by the collisions with the individual atoms (randomly positioned);

2. The rates increase with decreasing crystal temperature because the smaller thermal displacement amplitudes of the lattice atoms result in larger continuum electric field strengths.

Point 1) deserves some elaboration since it dictates the angular divergence requirement on the incident beam.

The CERN results[6,7] on Ge <110> show that the critical angle for the total CAP rate with ~90 GeV photons is $\gamma\theta \sim 7$. This agrees with the full quantum mechanical calculations[3] in which a scaling of $\theta \propto 1/\sqrt{\gamma}$ is also suggested. These calculations consider only final states which are bound to the atomic string. On the other hand, the total radiated energy measured with 150-GeV electrons shows a much larger critical angle of $\gamma\theta \sim 300$. We do not understand the difference. Coherent effects[13] may enter in the region of the critical angle since the angular scans were taken along a direction which emphasizes these coherent effects. The forthcoming CERN run may shed some light on this problem since we intend to scan in a direction which minimizes the coherent effects. In any event, current theories[14] on coherent bremmstrahlung and coherent pair production are based on the first Born approximation which breaks down at sufficiently small angles. For the conditions of the proposed experiments at Fermilab, it is unlikely that the coherent Born approximation is applicable. We are now working[15] on a new description of CAR and CAP, based on the semiclassical approximation, which gives the angular dependence of the yield.

Preliminary calculations show the critical angles for CAR and CAP to be the same with a value of $\gamma\theta \sim 80$ for 100 GeV in Ge <110>, and these suggest a scaling of $\theta \propto 1/\sqrt{\gamma}$. We would thus require the 800-GeV electron beam to have an angular divergence of $\lesssim 150$ μrad. The tighter the definition of the beam the better, since the detailed shape of the angular dependence of the rate will be important to the theories and applications. Below we comment on each of the measurements.

Crystal-Assisted Radiation (CAR)

The best argreements between measurements and predictions to date are obtained for radiation along axial directions. Already, for 150-GeV electrons in a LN_2-cooled Ge of 0.4 mm thick, the total radiated energy along <110> is observed(7) to be 25 times larger than for non-aligned directions. A much larger enhancement may be expected for 800 GeV electrons, and the results will test the CAR theory in a new region of $\chi > 1$ for which experimental information is absent. Measurements will also be made along the (100), (110) and (111) planes to obtain experimental rates upon which future polarization measurements can be based.

Crystal-Assisted Pair Creation (CAP)

The only experimental study(6) was with 50-100 GeV photons along LN_2 cooled Ge <110> where the rate begins to exceed the Bethe-Heitler (BH) value. The observed total rates of roughly 1/3 the predicted values can be understood only if the actual field strengths are lower than calculated. This can be seen in Figure 4 where the predictions based on the uniform field approximation are shown. At 100 GeV, the room temperature (RT) Ge CAP rate is equal to the BH value, while the corresponding cooled case with its higher field strengths is a factor of 3 larger. Thus, the CERN data agrees with the RT values when in fact the crystal was measured to be at a temperature of ~100^{o}K. The proposed measurements at 600 GeV at Fermilab will provide another check of the theory. At this energy the CAP rate is predicted to decrease only by 23% in going from 77K to 300K. With a 0.4-mm thick LN_2-cooled Ge crystal, the predicted rate at 600 GeV is ~0.17 pair/photon.

Planar CAP rates will also be measured because we need firm numbers to plan for future polarization measurements. For 600 GeV photons in a 0.4-mm thick LN_2-cooled Ge, the expected rate is ~0.037 pair/photon for the (110) plane.

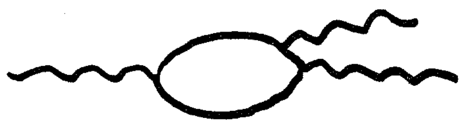
The electron and positron created in CAP remain in the large fields of the crystal, and thus will undergo CAR. In the planar case, these photons are expected to be plane polarized. Our set up will measure these radiative yields.

Crystal-Assisted Trident Production (CAT)

Trident production can be viewed as a sequence of CAR and CAP. In the uniform field approximation, the calculation of CAT rate requires the introduction of a path length parameter ℓ which serves to characterize the time interval of the sequential process[4,12]. The availability of experimental rates will greatly aid the development of a theory which does not require an arbitrary parameter. As mentioned earlier, CAT events can be recorded simultaneously with CAR events.

Crystal-Assisted Photon Splitting (CAS)

Photon splitting is the changing of a single photon into two real photons, and arises from a nonlinear correction to QED. The "Feynman" diagram of this process is



Here the particles are not free but are dressed particles. In sufficiently large fields, the photon-splitting absorption coefficient is given by[16]

$$\alpha(m^{-1}) = 3.2 \times 10^{-6} \left(\frac{h\nu}{mc^2}\right)E^*.$$

In the crystal fields of LN_2-cooled Ge <110> and W <100>, we obtained $\alpha = 5.1\ m^{-1}$ and $\alpha = 14.5\ m^{-1}$ respectively at 600 GeV. Using a crystal thickness of 3 mm, these correspond to 0.015 and 0.043 event/photon. The proposed use of a thin lead converter-plastic scintillator sandwich detector to differentiate one and two photon events may prove marginal for extracting accurate CAS rates of these magnitudes, but it should be adequate for observing any change in the two photon rate when the crystal is oriented from an aligned to a non-aligned direction.

III. Experimental Requirements

1. Electron Beam

   - Energy of 800 GeV.

   - Angular divergence of $\lesssim$ 150 μrad.

   - Diameter of 1.5 cm.

   - Intensity of 10^4 e^-/burst, or a few 10^7 e^-/day.

2. Beam Time

   - A few days for beam tuning.

   - One week for taking CAR and CAT data for axial and planar cases.

   - Two weeks for taking CAP and CAS data.

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Figure Captions

Figure 1: Relative enhancement $(W_A-W_{NA})/W_{NA}$ of the pair creation rate in a <110> Ge crystal. W_A and W_{NA} are the pair creation rates for aligned and non-aligned directions, respectively. The enhancement is shown as a function of incident photon energy and compared with the crystal-assisted theory.

Figure 2: The spectrum of total radiation energy produced by 150 GeV electrons aligned with the Ge <110> axis. The curves on bottom and top correspond to 1.4 mm and 0.4 mm target thicknesses. The unusual shape of the measured spectra and the variation with target thickness is interpreted as an indication of greatly enhanced radiation without significant absorption. Good agreement of the theory with experiment is obtained when the multiphoton nature of the spectrum is considered, a modified equilibrium flux distribution is assumed, and a 1 μm pathlength parameter is used. The results of inserting a Pb converter and veto out the charged pairs produced are also shown.

Figure 3: Schematic of the proposed experimental set up: R - radiator; M1 and M2 - magnets; S_t, S_b, S_{+1}, S_- and S_I - plastic scintillators; L_t,L_+ and L_- - lead glass detectors; CS1 and CS2 - alternating thin layers of lead converter and plastic scintillators; L_I - lead glass calorimeter.

Figure 4: Absorption coefficient for crystal-assisted pair creation along Ge <110> and W <100> based on the uniform field approximation. The solid curves are for a crystal temperature of 77K and the dashed curves for 300K. The corresponding Bethe-Heitler values are also indicated.

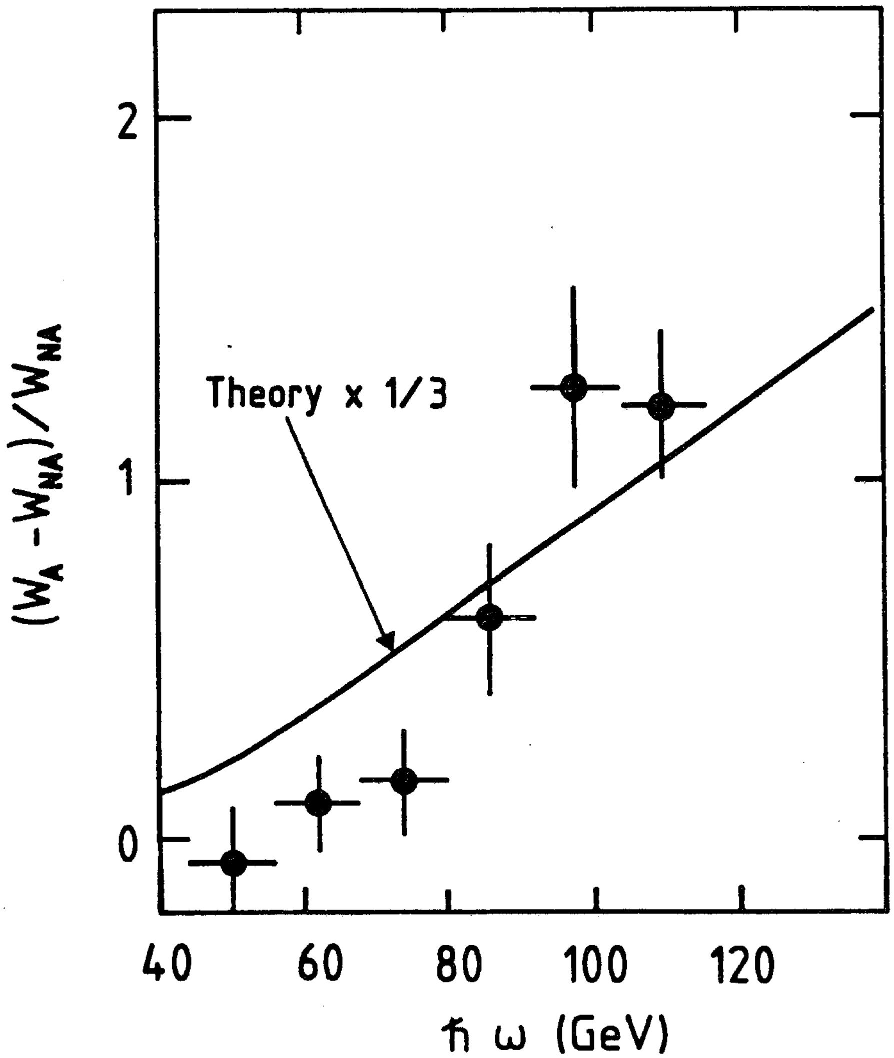
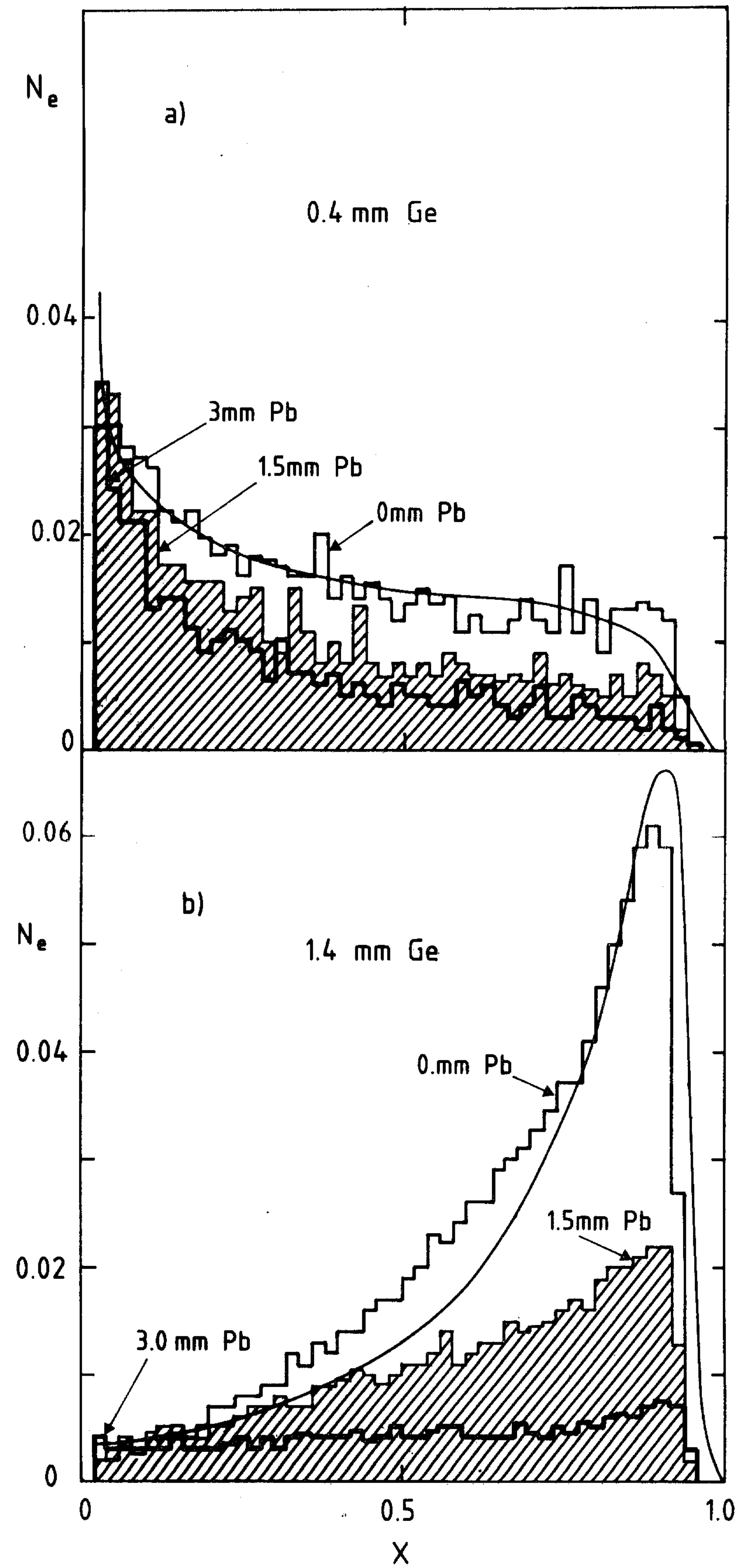


FIG. 1



N_e
a)
0.4 mm Ge
0.04
0.02
0
3mm Pb
1.5mm Pb
0mm Pb
0.06
b)
N_e
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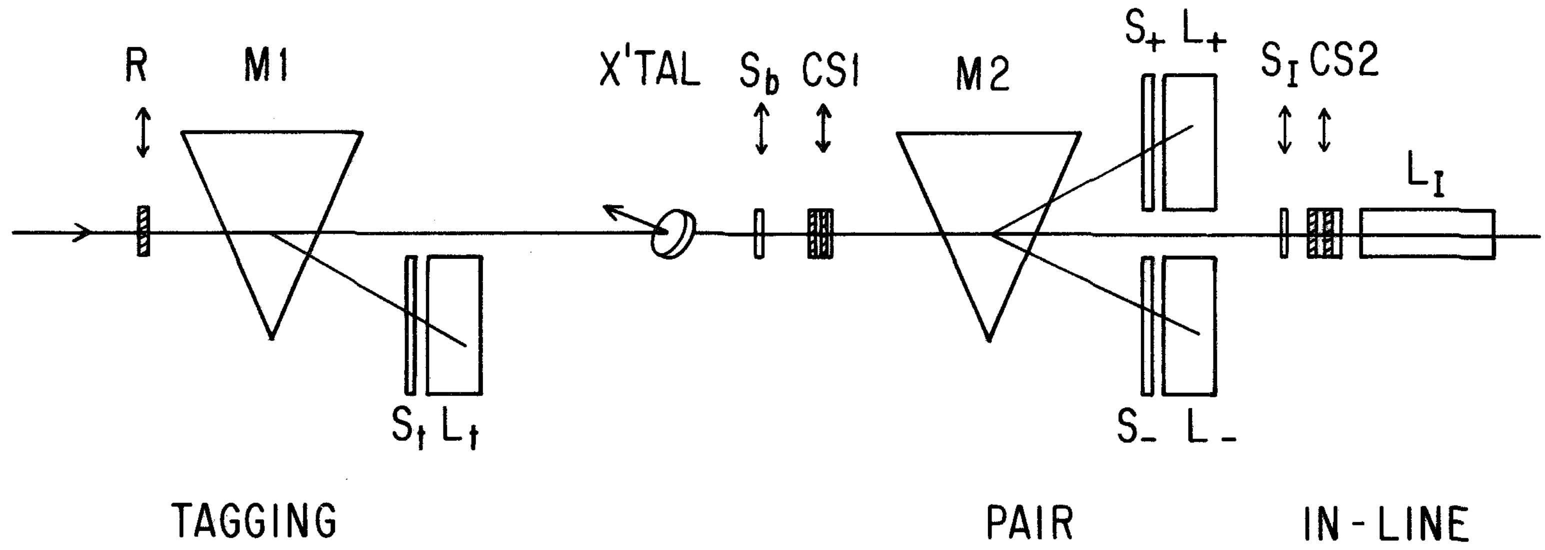
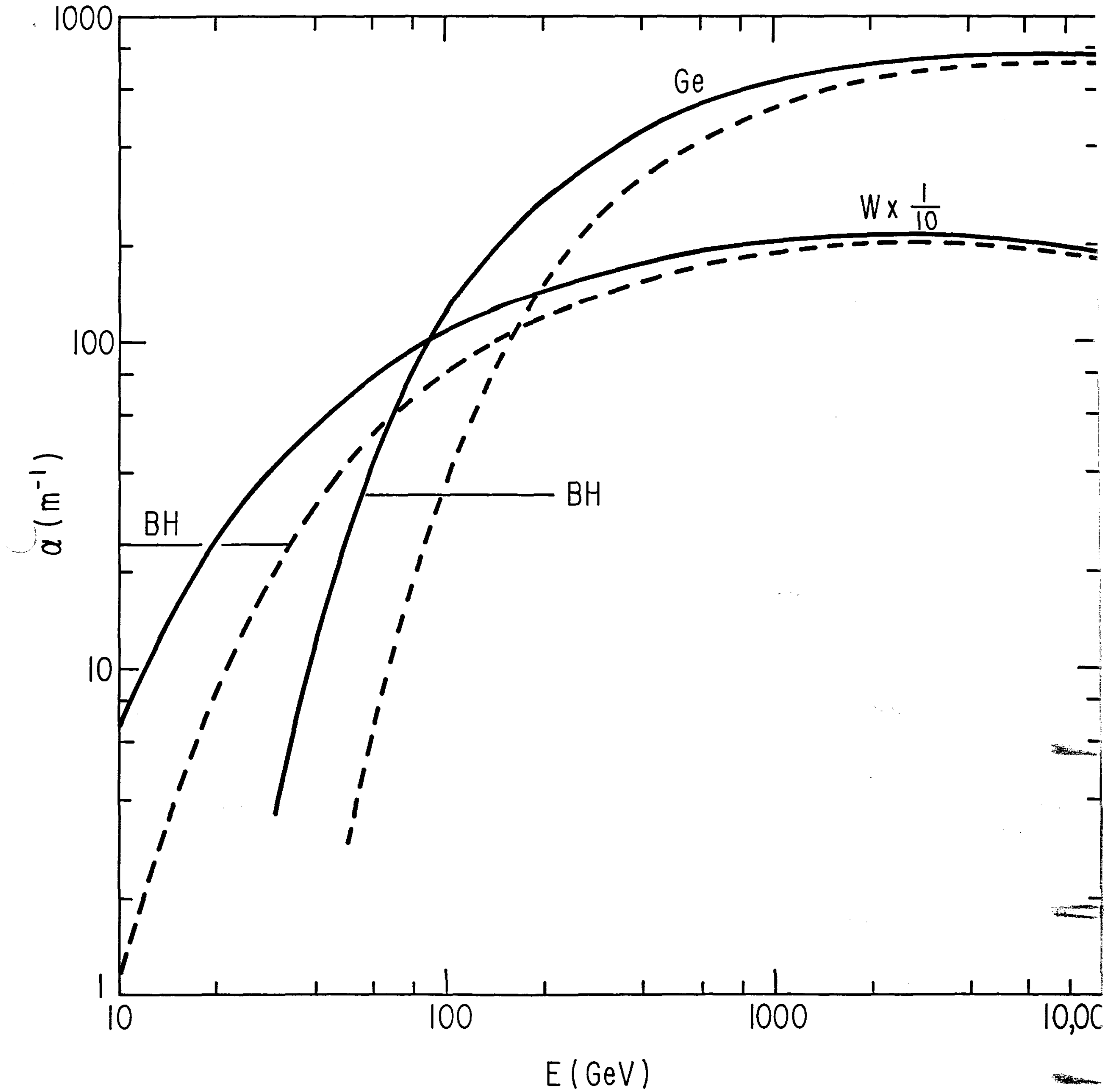
0.04
0.02
0
0.mm Pb
1.5mm Pb
3.0 mm Pb
0
0.5
1.0
X



	R	M1	S_t+L_t	S_b	CS1	M2	S_-+L_-	S_++L_+	S_I	CS2	L_I
CAR	x	x	x	✓	x	✓	✓	-	✓	✓	✓
CAT	x	x	x	✓	x	✓	✓	✓	-	-	-
CAN	x	x	x	✓	x	x	x	x	x	✓	✓
CAP	✓	✓	✓	✓	x	✓	✓	✓	✓	-	✓
CAS	✓	✓	✓	✓	✓	✓	✓	✓	✓	x	✓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E (GeV)

FERMILAB-Proposal-0739

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Measurements of Crystal-Assisted Electron-Positron Pair Creation

N. Cue, W.M. Gibson, I.J. Kim, J. Kimball
B.B. Marsh, C.R. Sun and R. Wijayawardana

Department of Physics
State University of New York at Albany

and

S. Baker, R. Carrigan, Jr., and T. Toohig

Fermi National Laboratory

Spokesmen: N. Cue, Tel: 518-457-8450
C.R. Sun, Tel: 518-457-8028

Summary

We propose to undertake experimental confirmation and detailed study of the recently predicted[1] mechanism of enhanced electron-positron pair creation by high energy photons (or charged particles) directed along crystallographic axes. In this case the crystal field in the solid lowers the energy of some electrons by the well established channeling effect, so that a photon can decay directly into an electron-positron pair without violating energy and momentum conservation. Viewed in the coordinate system of an energetic charged particle moving along a row of atoms, the effective field is very large because of the Lorentz contraction of the atomic spacing along the row. Unlike the centrosymmetric case, here the time averaged field increases with increasing speed of the particle, and thus may be of interest in investigations of other processes normally forbidden in free space by energy conservation.

The tagged photon facility at Fermilab, capable of delivering photons of 10-300 GeV with good beam properties, is particularly suited for this undertaking since no major alteration of the facility is required. A four-week and a two-week period of beam time with some reasonable lapse time in between are requested. The first period will be utilized for test runs, while data taking in final form is planned for the second. An electron beam of comparable energy, which can easily be switched in, may be required for crystal alignment and may also be used as the primary beam to induce pair creation in the crystal. Differential pair production rates will be measured as functions of the incident energy, pair energy, crystal tilt angle and temperature.

Measurements of Crystal-Assisted Electron-Positron Pair Creation

I. Introduction

A new electron-positron pair creation process is predicted[1] to occur when energetic photons (or charged particles) are directed along crystallographic axes or planes. In effect, the crystal field in the solid lowers the energy of some electrons by the well established high energy channeling effect[2], so that a photon can decay directly into an electron-positron pair while conserving both energy and momentum. Viewed in the coordinate system of an energetic charged particle moving along a row of atoms, the effective field is large because of the Lorentz contraction of the atomic spacing along the row. The process may thus be considered as a "strong field" process. Unlike the centrosymmetric field case, here the time averaged field strength felt by the particle increases with its velocity.

We propose to experimentally confirm the predicted process and examine its detailed features. The experimental results will then provide important benchmarks for the extension of the theory to other processes in the crystal field, as well as a firm basis for applications to accelerator physics. In Section II, the theoretical background is given in order to set the stage for describing the proposed measurements which are detailed in Section III. Perceived significance of the proposed work to particle physics at high energy is covered briefly in Section IV.

II. Theoretical Background

The theoretical motivation for this experiment will be discussed only in brief, since details are presented elsewhere[1,3,4]. We wish to describe the newly predicted aspects of pair production which should be observed when a photon is directed along a crystallographic axis. The key to visualizing crystal-assisted pair production is the existence of special two-dimensional bound-electron states in crystals. Channeling experiments have shown that for many applications, the electrostatic potential in the crystal can be averaged along the direction of rapid motion (z-axis). This results in a two-dimensional "string potential" which can trap electrons in two-dimensional bound states even though the electrons move rapidly along the z-axis. Ordinarily, photons cannot spontaneously decay into electron-positron pairs while conserving both energy and momentum. However, if the photon can decay into a positron plus a bound electron with reduced energy, then the spontaneous decay can occur.

The crystal-assisted pair production process is illustated using the dispersion relations of Fig. 1. The upper and lower curves in this figure show the positive and negative frequency free-particle solutions to the Dirac equation as functions of the momentum along the z-axis (motion along x and y is considered negligible). The two-dimensional bound-electron states are also shown as the curve displaced downward by a binding energy $|\epsilon^-|$ from the free-electron dispersion curve. The size of the binding energy is exaggerated in this figure.

Pair production takes place when the photon, shown as the wavy line in Fig. 1, elevates the negative energy state to a positive energy bound state. By directly absorbing the photon's energy and momentum, the particle makes a transition in a direction parallel to the photon dispersion curve labeled as the photon line. A Feynman diagram illustrating the process is the insert to Fig. 1. The electron final state in the Feynman diagram is shown as a heavy line to emphasize its bound-state character. This new process should be contrasted with other pair production mechanisms in which momentum and energy are conserved through scattering rather than an alteration of the character and energy of the final states[5].

One can see from Fig. 1 that there is a minimum photon energy necessary for the new crystal-assisted pair production to take place. For highly relativistic particles, the expression

$$E = \sqrt{(mc^2) + (pc)^2}$$

can be expanded to lowest order in mc^2. Then a photon can elevate a negative energy state to a bound state only if

$$|\epsilon^-| \gtrsim \frac{mc^2}{2}\left(\frac{1}{\gamma^-} + \frac{1}{\gamma^+}\right) ,$$

where $\gamma^{\pm}$ are the relativistic factors, $E^{\pm}/mc^2$, for the electron and positron. For a typical crystal, $|\epsilon^-| \simeq 100$ eV, and this gives a minimum photon energy of about 5 GeV. Detailed calculations show that a significantly larger energy is needed before crystal assisted pair production becomes the dominant process.

A quantitative calculation of the new pair production rate, W, is based on the Golden Rule

$$W = \frac{2\pi}{\hbar} \sum_{\text{final states}} |M|^2 \, \delta(E_{final} - E_{initial}),$$

where M is a transition matrix element and the delta-function ensures conservation of energy. The matrix elements can be obtained by adding the photon field to the Dirac equation which describes the electrons and positrons subjected to the crystal's string potential. These matrix elements are related to the spatial overlap of electron and positron wavefunctions. This overlap is small because the string potential which binds the electron repels the positron. When the incident photon is directed precisely along a crystal axis, this overlap is non-zero only because of barrier penetration in the transverse plane.

The results of calculations[3)] of the crystal-assisted pair production rates are shown in Fig. 2 for a number of different crystals. In each case, the rate is normalized to the corresponding Bethe-Heitler solution. Clearly, photon energies currently available at Fermilab are sufficient to observe the new mechanism described here.

Beside the enhanced absolute rate at high photon energies, crystal-assisted pair production is characterized by several distinctive features. Detailed calculations[4] show the high pair production rate should be observed only when the photon is aligned with a crystallographic axis to within an angle Θ_c which is a few tens to a few hundreds of microradians. More precisely, for diamond along the <110> axis, $\theta_c \simeq 1800/\sqrt{\gamma}$ μrad with γ being the incident photon energy in units of electron rest mass. Unlike the case of Bethe-Heitler theory, it is most likely that the electron and positron obtain roughly equal shares of the incoming photon energy. This is illustrated in Fig. 3 which shows the calculated distribution of created positron energies is peaked at 1/2 the incident photon energy. The physical basis for this effect can be seen in Fig. 1, since a photon can most easily directly couple positive and negative energy states which have comparable energies. Finally, one should note that the string potential depends on temperature since the atomic vibrations "smooth out" the averaged potential as the temperature is increased. Some typical examples of the temperature dependence of the predicted pair-production rate[3] are shown in Fig. 4.

The new aspect of this theory which makes crystal assisted pair production evident is the special treatment of the crystal's electrostatic potential. The crystal field is included in the zero-order Hamiltonian, and only the coupling to the photon is treated as a perturbation. This is necessary, because in some sense, averaged electrostatic string potentials encountered in real materials are not small. A coordinate system moving with the center-of-mass of the electron-positron pair "sees" a very large static electric field because of the Lorentz contraction of the distance between atoms in the z-direction. The field is enhanced by a relativistic factor γ which can be greater than 10^5 for photon energies available at Fermilab. The resulting effective electric fields are so large that pair production through tunneling (the Klein paradox) is a possibility. The analogy to the Klein paradox is not entirely fanciful. As was mentioned earlier, a calculation of the transition matrix elements, M, reduces to an effective barrier penetration problem. In practice, many of the results presented here utilized the Klein paradox analogy by linearizing the electrostatic string potential in the region of barrier penetration[3].

III. Proposed Measurements

The goal of the proposed undertaking is two-fold: to see whether or not the newly predicted pair creation mechanism can be realized in practice and, if affirmative, to check the accuracies of the various theoretical predictions. As detailed in the previous section, the predicted features are distinctive: 1)there is an effective threshold energy for the process which depends on the crystal type and axis; 2)the production rate depends strongly on the incident photon energy and crystal tilt angle (for a reasonably small beam divergence); 3) the production rate exceeds that of the corresponding ordinary mechanism by more than an order of magnitude at high energy; 4) there is a temperature effect; and 5) the pair distribution at perfect alignment is peaked for events in which the electron and positron share the energy nearly equally. Experimental verification of these features would constitute a valid test. The primary requirement is an energy tunable photon beam in the range of 10-300 GeV with reasonable angular divergence and energy resolution. Such a photon beam is currently available in the U.S., only at the Fermi National Laboratory with the Tagged Photon Beam (TPB) Facility there.

Specific to the TPB facility at Fermilab, two possible layouts are suggested and schematically illustrated in Fig. 5. Both require only minor alterations to the existing facilities, and the suggested additions or modifications are shown boxed in. In Scheme 1, the present tagging system will be used as a e^+ spectrometer, the crystal target attached to a goniometer will be located at the present $e^- - \gamma$ converter position, and the last upstream magnet will be converted into a photon tagging system. In Scheme 2, we will put the goniometer in the space between the shielding wall and the existing spectrometer. We could use one or both of the dipole magnets of the existing spectrometer system (or alternatively, install a new magnet in the space as shown in Fig. 5) to deflect the e^+ and e^- from the pairs created in the crystal. We plan to place two small (3"x6"x20") drift chambers which we have on hand at some accessible locations in the gaps of the existing spectrometer such as shown in Fig. 5. We feel that these installations will not perturb the existing spectrometer system. The magnet(s) and our own drift chambers together will serve as a spectrometer for the e^+e^- pairs. Momentum resolution of about 10% will be enough to establish the effect. Scheme 2 is preferred because: 1) the beam geometries are known in detail, 2) the beam spot size at the target position is smaller and makes possible the use of small size crystals, and 3) e^+-e^- coincidence measurements are more readily implemented if and when needed. Although our primary interest in this proposal is the tagged photon beam, the ready availability of an electron beam may prove essential for the alignment of the crystal target. Furthermore, crystal-assisted pair production with incident electrons is of interest in itself. Initial measurements will be confined to Ge because single crystals with a mosaic spread of $\leq 10\mu$rad are available. Based on the experience gained in previous studies of high energy channeling motion and channeling radiation[2], we do not anticipate any unusual problems with crystal alignment, particularly since an electron beam can be easily switched into the same setup. Of course, once the crystal-assisted pair creation mechanism is proven, it can be used to align the crystal.

In order to give some estimate of the beam time required and the optimal set of measurements to be performed, we compute the expected pair production rate as follows: We request 10^{11} protons per pulse at 900 GeV (or 2.5×10^{12} protons per pulse at 400 GeV). This will give us about $2.5 \times 10^{-5} \times 10^{11} \doteq 2.5 \times 10^{6}$ e^{-}s at 200 GeV. Using a 20% radiator, we expect to get $0.12 \times 2.5 \times 10^{6} \simeq 3 \times 10^{5}$ tagged photons, (or $\sim 10^{5}$ for a 5% radiator) in the range from 50-200 GeV. If we take photons at $E_{\gamma} = 100 \pm 10$ GeV, we will get 2×10^{4} photons/pulse.

To do the experiment, we need to have the beam divergence adjusted to $\sigma_{\theta_x} = \sigma_{\theta_y} \simeq 50\,\mu$rad. We understand that the present beam is more divergent than this. Detailed information as to the capability of tuning the beam is not available. If the beam cannot be tuned to be more parallel, we propose to reduce the divergence by collimating either the e^{-} or the photon beam. A very conservative estimate is that the photon yeild will be reduced by a factor of 100 giving $2 \times 10^{4}/100 = 200$ photon/pulse at 100 ± 10 GeV, with angular divergence of $\sigma_{\theta_x} = \sigma_{\theta_y} \simeq 50\,\mu$rad, in a spot size $\sigma_x \simeq \sigma_y \simeq .9$ cm. All these photons are intercepted by the crystal within the critical angle.

A 5-mm thick Ge target will be used, with the beam direction along the 110 axis. For Germanium $\alpha_{BH} = 32.8\ \mathrm{m}^{-1}$, and from Fig. 2, $\alpha/\alpha_{BH} \simeq 10$. This implies about 80% of an ideally aligned beam would undergo crystal-assisted pair production in a 5-mm crystal. Setting the positron spectrometer for 50 GeV and taking a 10% momentum bite will detect about 20% of the produced positron flux. Thus, the idealized count rate is ~~(2 x~~ (200/pulse) x (0.8) x (0.2) = 32 e^{+}/pulse. The background rate from the ordinary pair production mechanism in the same target will be down by a factor of more than 10 because its distribution function is comparatively flat relative to the crystal-assisted case. The detection of positrons rather than electrons avoids the general background of delta rays. Germanium was chosen for illustration because excellent single crystals of appropriate size are commercially available.

Given that the counting rates are reasonable, two periods of beam time are requested. The first period of four weeks will be needed to align the beam, check the sources of background, test the equipment, align the crystal and perhaps execute the first data run. A reasonable time lapse before the next period of two weeks would be prudent if improvements suggested by the experience gained in the first period are to be implemented before taking data in the final form. In the data acquisition, the following sequence is planned: 1) for $h\nu$ = 100 GeV and a beam divergence of 50 μrad, set the e^+ spectrometer to accept $E^+ = 1/2\ h\nu$ and record the pair rate $d\alpha/dE^+$ versus the crystal tilt angle for Ge $\langle 110 \rangle$; 2) if the crucial test in Step 1 is affirmative, adjust the beam angular divergence to be as small as practical, and map out $d\alpha/dE^+$ versus E^+ and θ 3) measure the excitation function for Ge in the appropriate energy range suggested in Fig. 2; 4) measure the temperature dependence of $d\alpha/dE^+$; 5) if time permits, measure crystal-assisted pair production using incident electrons instead of tagged photons.

IV. Construction and Equipment Needed

For Scheme 1, a moderate modification of the beam line as shown in

Fig. 5 will be needed. For Scheme 2, there is no modification of the beam line. We will provide the goniometer, drift chambers and the read-out, and the counters needed. The need for the PREP equipment is very modest and is less than that used by E660.

V. Relevance to High Energy Physics

Experimental confirmation of the crystal-assisted pair creation process with incident photons is essential if the applications of the new process are to be pursued. Aside from providing a benchmark for the theory with incident photons, it will also provide a firm footing for extending the theory to the case of incident charged particles. Already we can envision immediate applications. For example, in the tagged photon facility at the Fermi National Laboratory, the electron intensity could be enhanced through use of a photon converter in the form of a properly aligned crystal. Thus, a corresponding increase in tagged photon flux may be expected. Although detailed predictions of the e^+-e^- pair production rate for incident electrons and positrons are not yet available, the crystal assisted rate nevertheless is expected to be enhanced over that from a corresponding polycrystalline or amorphous target.

Crystal-assisted pair production is an example of an effect which can best be described in terms of strong external fields instead of perturbation theory. Such an example should stimulate investigations of the effects of the crystal environment on particle physics. For example, the process $\pi^- \rightarrow \pi^- + (e^- + e^+)$ can take place in a tungsten crystal field with a kinematic threshold energy $\sim$85 GeV.

Addendum:

We have learned that the group headed by Claude Bovet of CERN now uses a single crystal as a γ-e^- converter in their tagged photon facility (NA1) to routinely obtain a 16-22% enhancement in the electron flux. A telephone call to CERN on June 6, 1983, confirmed this fact. However, the information they provided us suggests that the setup they have and the conditions with which they have been operating would make it unlikely for them to see the effect proposed here.

References

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3. J. Kimball and N. Cue, to be published in the Proceedings of the 10th International Conference on Atomic Collisions in Solids, July 18-22, 1983, Bad Iburg, West Germany.

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5. G.D. Palazzi, Rev. Mod. Phys. 40, 611 (1968).

Figure Captions

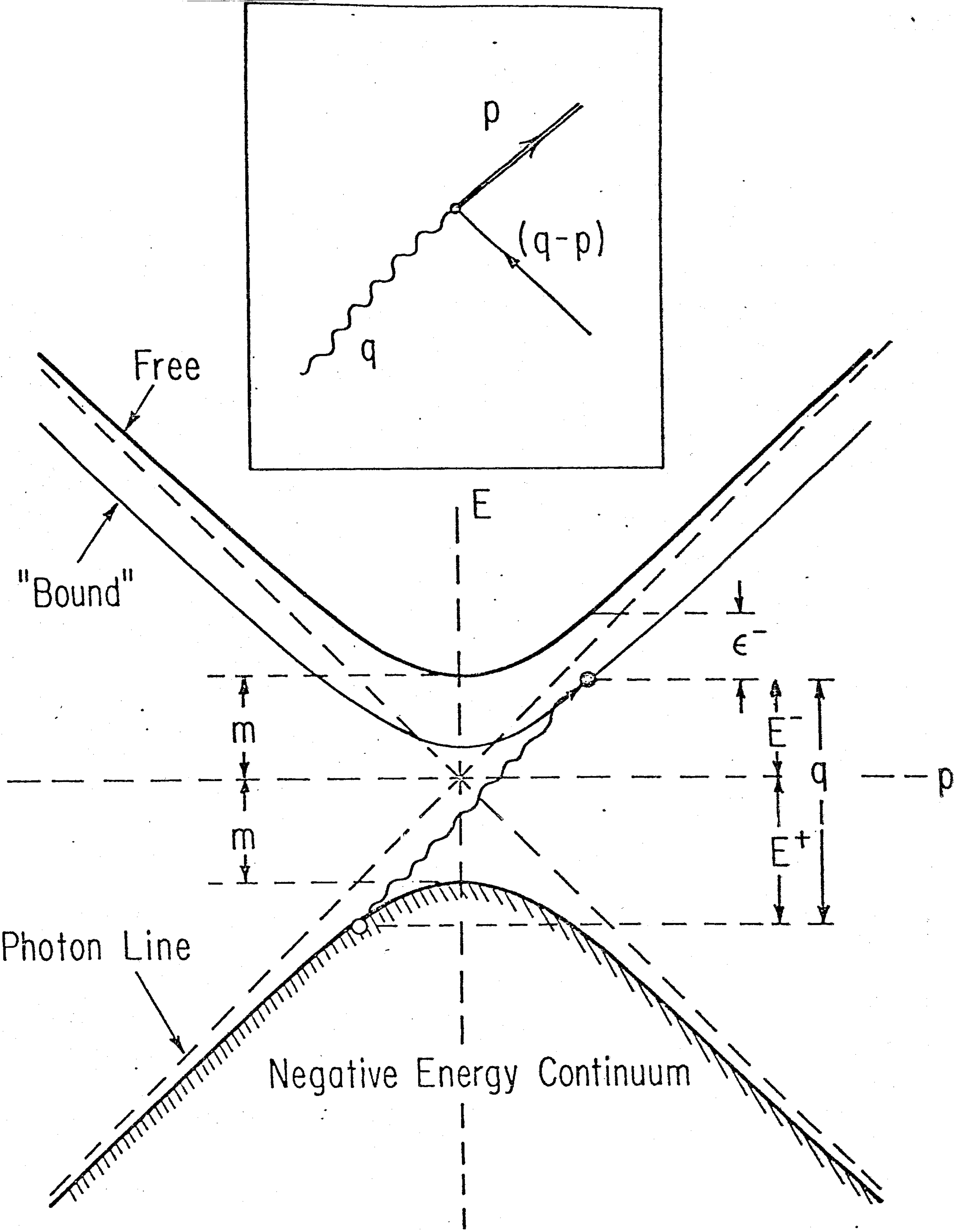
Figure 1 - A one-step process of electron positron pair creation for an incident high energy photon directed along a crystal axis. Both energy and longitudinal momentum are conserved in exciting an electron from the negative-energy continuum to a positive-energy channeling state. (The binding energy has been exaggerated.) The corresponding Feynman diagram is shown in the insert.

Figure 2 - Theoretical absorption coefficients (inverse mean-free-path), α, for the process described in Fig. 1 in various crystals at room temperature are shown normalized to their corresponding Bethe-Heitler values as functions of the incident photon energy. Perfect alignment along the strongest channeling axis is assumed in each case.

Figure 3 - Computed energy distributions of created positrons for 26-, 51- and 102-GeV photons aligned exactly with the $\langle 110 \rangle$ axis of diamond.

Figure 4 - Predicted temperature dependence of α for photons exactly aligned with diamond $\langle 110 \rangle$ and W $\langle 111 \rangle$ at several energies.

Figure 5 - Schematics of proposed experimental arrangements using the existing Tagged Photon Beam Facility at Fermilab.



p
(q-p)
q
Free
"Bound"
E
ϵ^-
m
m
E^-
q
p
E^+
Photon Line
Negative Energy Continuum

FIGURE - 1

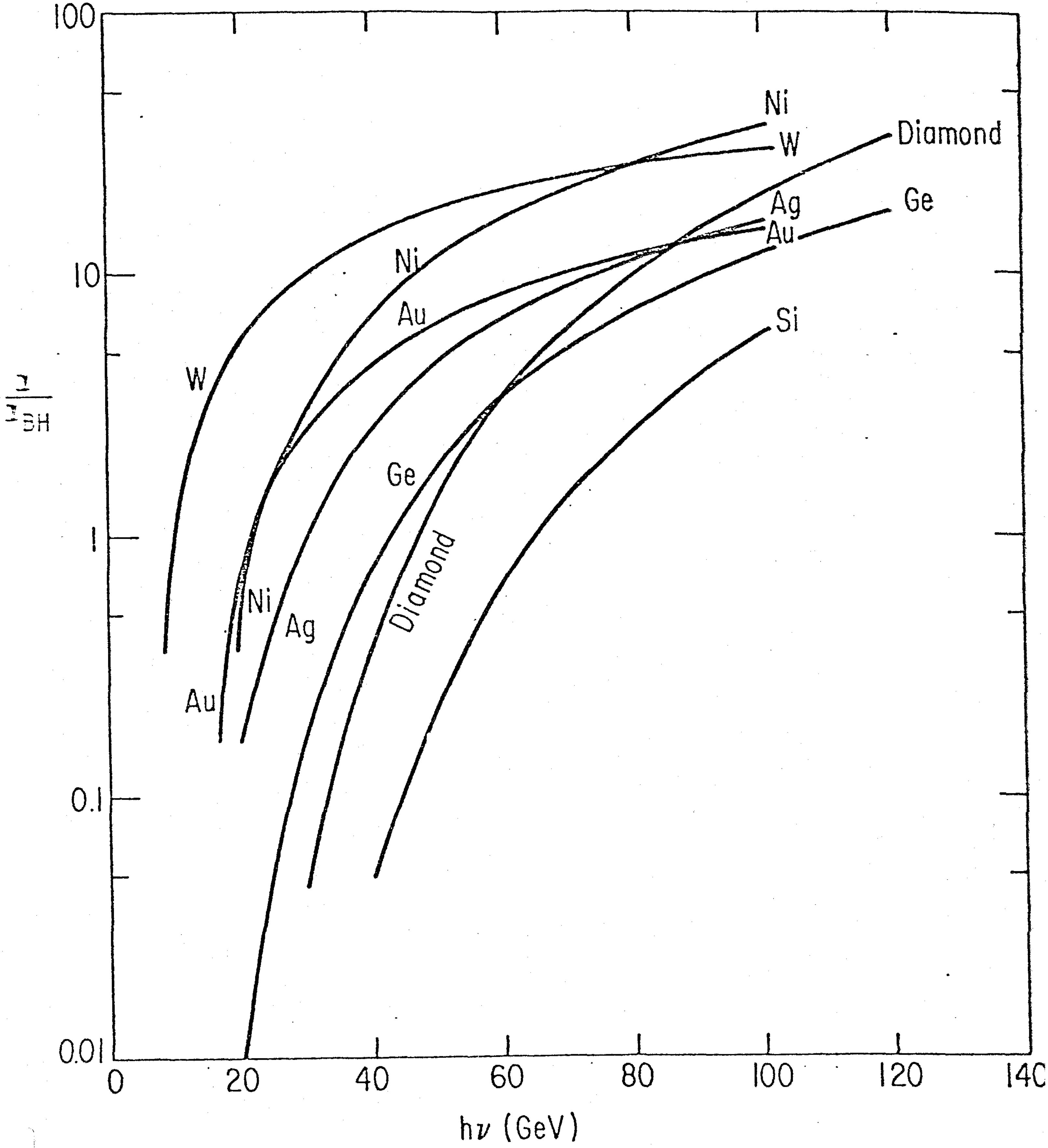
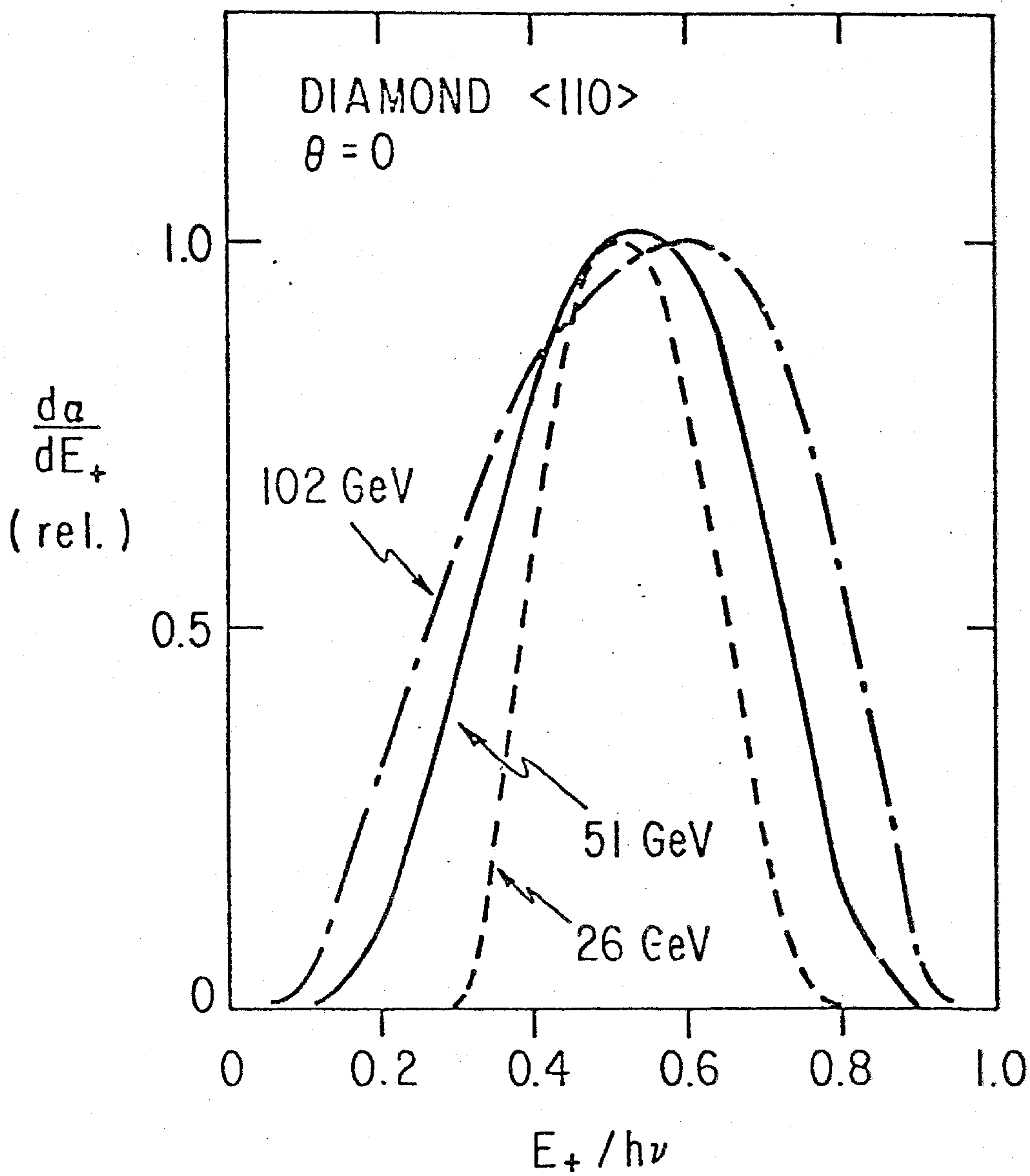

100
10
1
0.1
0.01
0
20
40
60
80
100
120
140
hν (GeV)
W
Ni
Au
Ag
Ge
Diamond
Si

FIGURE - 2


DIAMOND <110>
θ = 0
1.0
0.5
0
dσ/dE₊ (rel.)
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51 GeV
26 GeV
0
0.2
0.4
0.6
0.8
1.0
E₊/hν

FIGURE -3

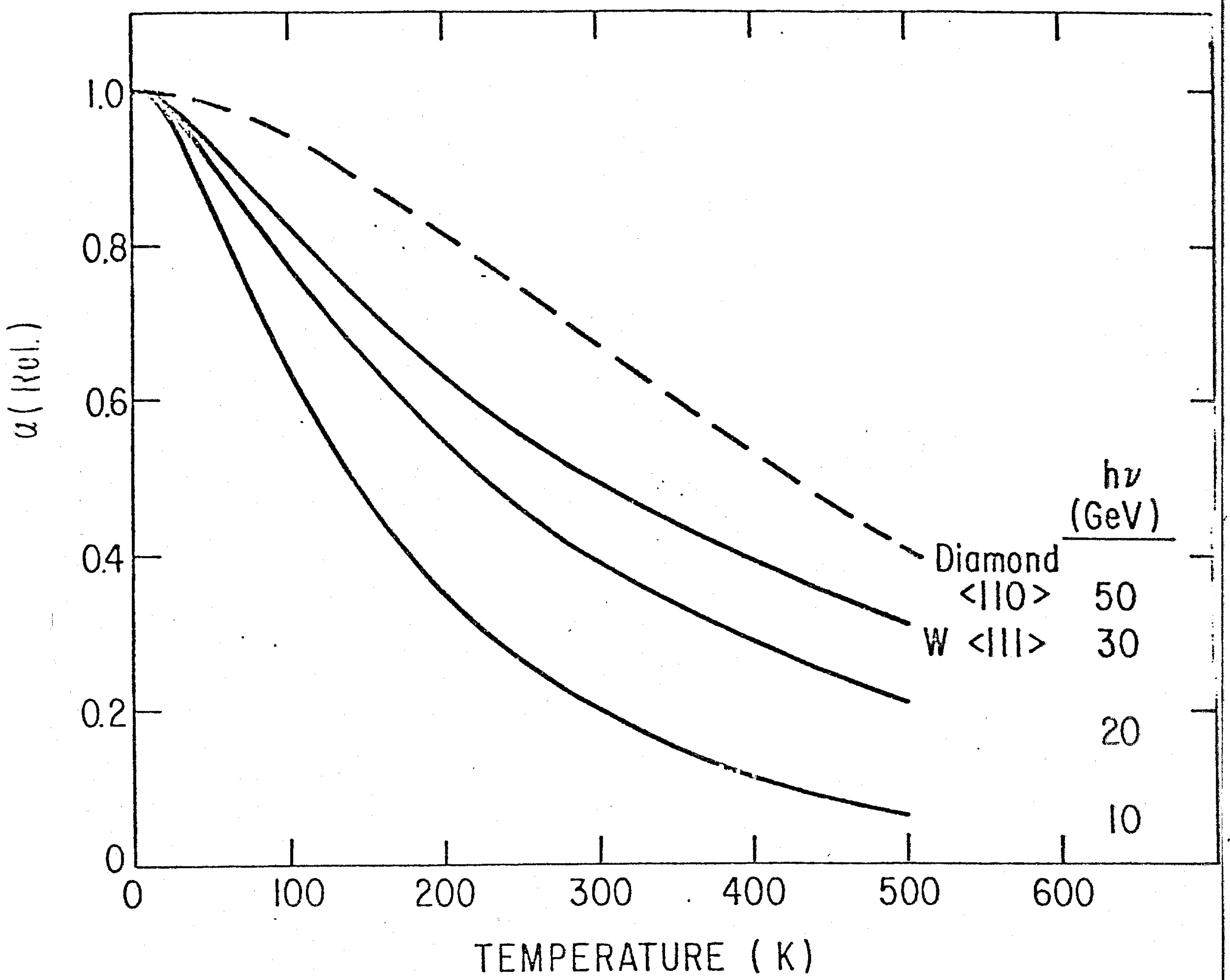
1.0
0.8
0.6
0.4
0.2
0
a (Rel.)
0
100
200
300
400
500
600
TEMPERATURE (K)
hν
(GeV)
Diamond
<110>
W <111>
50
30
20
10

FIGURE - 4

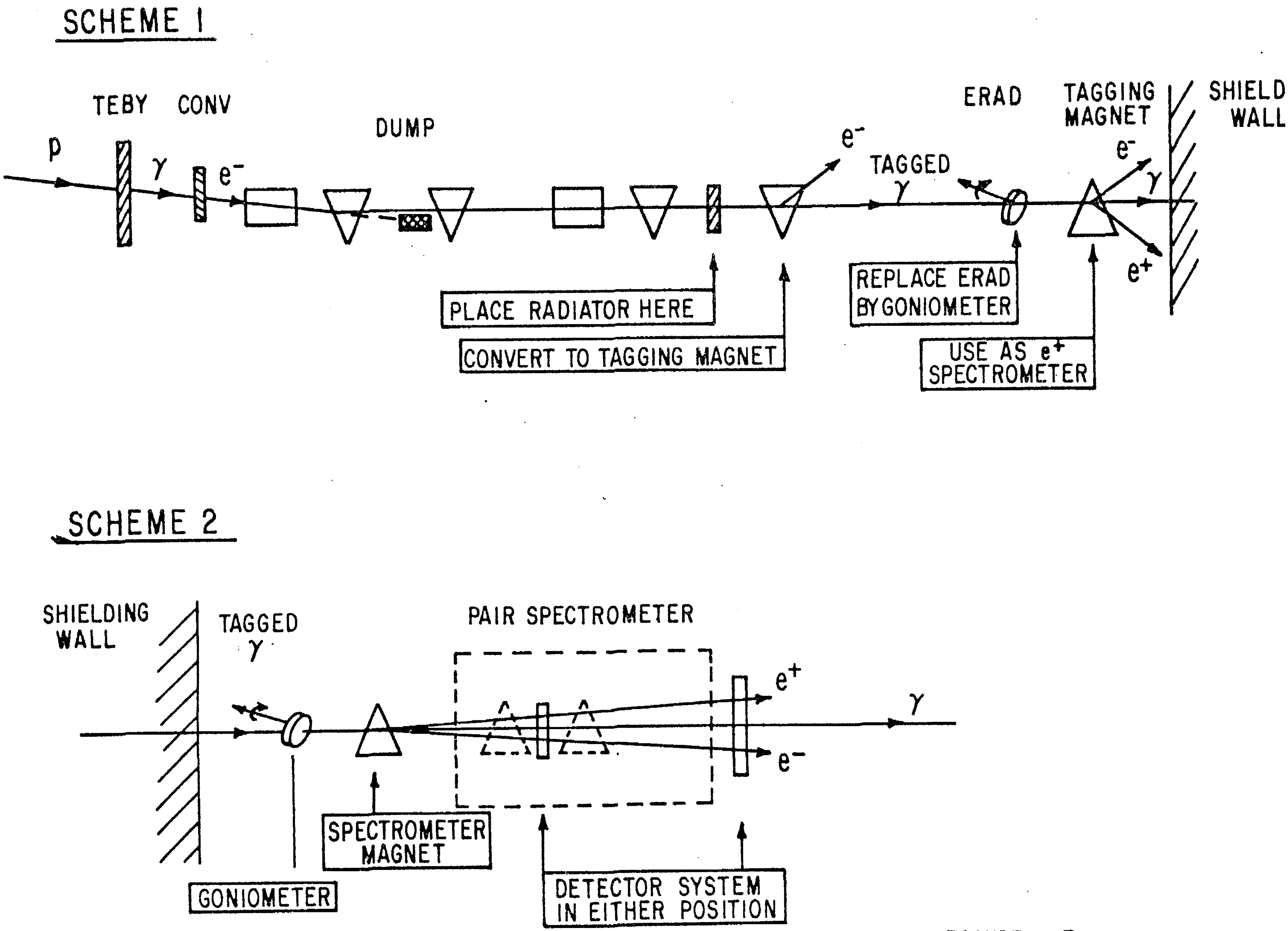
SCHEME 1
p
TEBY
γ
CONV
e⁻
DUMP
PLACE RADIATOR HERE
CONVERT TO TAGGING MAGNET
e⁻
TAGGED γ
ERAD
REPLACE ERAD BY GONIOMETER
TAGGING MAGNET
USE AS e⁺ SPECTROMETER
e⁻
γ
e⁺
SHIELD WALL
SCHEME 2
SHIELDING WALL
TAGGED γ
GONIOMETER
SPECTROMETER MAGNET
PAIR SPECTROMETER
DETECTOR SYSTEM IN EITHER POSITION
e⁺
e⁻
γ

FIGURE - 5